DECAF – Density Estimation for Cetaceans from passive Acoustic Fixed sensors

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LONG-TERM GOALS

Determining the spatial density and distribution of cetacean (whale and dolphin) species is fundamental to understanding their basic biology, and also to monitoring and mitigating the effect of man-made impacts on their populations. However, this task is difficult because most cetacean species occur at low density and over enormous areas, and because they spend relatively little time at the surface where they can be seen using standard, visual surveys. Our primary long-term goal is to develop and test methods for estimating cetacean density based on detecting the sounds cetaceans make underwater, using fixed hydrophones.

OBJECTIVES

1. Develop statistical methods for estimating the spatial density of cetacean species from fixed passive acoustic devices. Methods should be applicable to a wide range of scenarios, including dense and sparse arrays of permanent, bottom-mounted sensors and single bottom-mounted or floating sensors.

2. Demonstrate the utility and generality of the methods by implementing them in a set of key test case studies. These test cases will also focus the methodological development to ensure their relevance to real-world applications. We aim as far as possible to leverage data that have already been collected, and acoustic detection, classification and localization methods that have already been developed.

3. Promote adoption of the new methods in the marine mammal research community by (a) publishing results in the peer-reviewed literature, (b) archiving data and results in publicly available electronic storehouses (e.g., the Ocean Biogeographic Information System, OBIS SEAMAP), (c) holding one or more workshops open to all interested researchers (participants at these will be self-funded).

APPROACH AND WORK PLAN

Technical approach

In developing the statistical methods, we are building upon the existing substantial body of work on distance sampling survey methods (e.g., Buckland et al. 2001, 2004). Fixed passive devices are conceptually most similar to a type of distance sampling called point transect sampling. However, there are several important issues that prevent a straight application of existing methods, as described in the project proposal and in Thomas and Martin (2006). We are developing methods to address these issues through a series of case studies. Our basic approach in each case is to develop the new statistical methods required for the situation and to apply the methods using acoustic data that has already been collected (but in most cases will require processing). In doing this, we are leveraging the very significant efforts already expended in data collection, and also in the development of methods for data processing and analysis. We stress that although we will be analyzing specific datasets, our methods are designed to be general.

The case studies are as follows.

- *Estimation of beaked whale density at the Atlantic Undersea Test and Evaluation Center (AUTEC) range, Bahamas.* Beaked whales are deep-diving animals that produce echolocation clicks to locate prey at depth (like bats do in air). These clicks are received at a widely-spaced (4km) array of 82 bottom-mounted hydrophones at AUTEC, and a great deal of previous work has gone into

developing a system to process the sounds and quantify the number of clicks received. Because the sounds are highly directional, each is usually received less than three hydrophones, making it difficult to pinpoint the location of the animal producing the sound. Instead, we intend to use information from tagged whales to turn the number of clicks into estimates of animal density.

- *Estimation of minke whale density at the Pacific Missile Range Facility (PMRF), Hawai'i.* Minke whales are very cryptic to visual observers in the waters around Hawai'i, but they can be heard in late winter, when they call with a characteristic "boing" sound. The function of this sound is not known, but it may be a male display. A single boing can be heard on multiple hydrophones at the PMRF facility, which, together with the shallow-diving behavior of minke whales, makes this a contrasting case study to the previous one. We intend to use an array of about 20 bottom-mounted hydrophones spaced approximately 8 km apart to estimate density.
- *Estimation of sperm whale density at AUTEC.* Sperm whales produce very loud echolocation clicks. In contrast to beaked whales, these sounds are loud enough to produce significant bottom and surface echoes, and also to enable successive clicks from the same individual to be picked up on multiple hydrophones. We plan to develop methods that allow filtering out of echoes as well as association of successive clicks into "trains", thereby allowing estimation of the number of diving animals in a group, and hence (assuming all groups are heard at AUTEC) animal density.
- *Estimation of beaked and sperm whale density at AUTEC using single hydrophone data*. With a single hydrophone, many of the previous methods are not feasible. We plan to investigate the estimation of detection radius around single sensors using models of source sound levels, acoustic propagation and detector characteristics. We also intend to try exploiting the echoes from sperm whale clicks to estimate the distance at which clicks can be heard. Both approaches can lead to estimates of animal density given information about click rates.
- *Estimation of humpback whale density at PMRF*. This objective was in our proposal, but was replaced by the minke whale study (see above) because we found it would not make a good case study, for reasons outlined in the 2008 annual report. We will re-examine estimation of humpback whale density if time permits.

Project investigators and roles

The research is being undertaken by an internationally-leading, multi-disciplinary team of statisticians, acousticians, cetacean survey specialists and biologists, drawn from academia and the US military. In summary, our major roles are as follows:

- University of St. Andrews (UStA), St. Andrews, UK. Dr. *Len Thomas*, is project PI, and is collaborating with Dr. *Tiago Marques* and Dr. *David Borchers* on development of the new statistical methods and testing by simulation. Overall project management and coordination across all institutions is performed by Dr. *Catriona Harris*.
- Space and Naval Warfare Systems Center (SSD), San Diego, CA. Mr. *Steve Martin* is overseeing the test cases based on data from PMRF. Martin was PI on the ONR-funded project to collect these data.
- Oregon State University (OSU), Newport, Oregon. Dr. *David Mellinger* is developing an automatic classifier for minke and humpback whales; he is also taking the lead on developing methods for estimating density from single fixed sensors, together with post-doctoral research assistant Dr. *Elizabeth Küsel*.
- Naval Undersea Warfare Center (NUWC), Newport, RI. Mr. *David Moretti* is leading a team of engineers and acousticians, including Ms. *Jessica Ward*, Dr. *Ronald Morrissey*, Ms. *Nancy DiMarzio*, Ms. *Susan Jarvis*, and Dr. *Paul Baggenstoss*. They are using new detection algorithms

developed under this project, and capability previously developed under the Marine Mammal Monitoring on Navy Ranges (M3R) program, to extract and process data required for the case studies. They are also integrating data from animals fitted with acoustic tags with data collected on range hydrophones to estimate probability of detecting vocalizations, and other quantities, as well as participating in development of methods for density estimation.

- Woods Hole Oceanographic Institution (WHOI), Woods Hole, MA. Dr. *Peter Tyack* is providing estimates of vocalization behavior and movement data for sperm whales and beaked whale species required to convert estimates of click density to estimates of animal density. He is also collaborating on analysis of tagged whale data.

In addition to the core team of investigators, there is a project steering group of acknowledged experts in the above fields, who provide annual feedback on progress and advice on future directions. The steering group is Dr. *Jay Barlow* (NOAA Southwest Fisheries Science Centre), Prof. *Stephen Buckland* (University of St. Andrews) and Dr. *Walter Zimmer* (NATO Undersea Research Centre).

Work plan for coming year

2010 marks the final year of the project, which is due to finish in May. We have met or exceeded all of the milestones set for 2009 (see Work Completed, below), and we plan to capitalize on this success in the final months of the project. Our focus will be on writing up for publication the results we have generated this year and on completing the remaining case studies. We also anticipate producing a review paper describing how the various methods relate to one another, with initial thoughts on which to use when. We plan to hold a third open meeting on the subject area in 2010, this time as a special session at the Acoustical Society of America (ASA) conference on April 19th-23rd in Baltimore, MD. We also plan to old another such meeting in 2011; although this will happen after the DECAF project has finished, it demonstrates that momentum built up by this project is likely to continue.

WORK COMPLETED

Beaked whale case study. We wrote up, submitted, and published our work on the cue-counting analysis of beaked whales at AUTEC discussed in our 2008 report (Marques et al. 2009). We undertook a dive-counting analysis of a dataset based around a Navy training exercise, looking for effects of range activity on beaked whale density, as measured acoustically. This study was presented at a conference in Pavia, Italy (see below) and we are currently writing this up for publication.

Minke whale case study. We have developed an automated detector capable of recognizing minke whale boings that could be used generally to classify tonal sounds. The detector was ported to the M3R processor which allowed large PMRF data sets to be efficiently analyzed. This was presented at the Pavia conference, and is being written up for publication. We have undertaken a simulation study comparing two different estimation approaches, both based around a recently-developed technique called spatially explicit capture recapture (SECR, Efford et al. 2009). This was presented at an international statistical ecology conference, EURING, in Pescara, Italy, and is also being written up. For our main case study analysis, we have selected a sample of 11 days of data from February to April 2006 and have processed it using the boing detector. For a smaller sub-sample, we have associated calls across hydrophones, and are now in a position to use SECR-based methods to estimate density.

Sperm whale case study. We have developed algorithms for recognizing echoes, for grouping clicks into trains, and for associating trains across multiple hydrophones to allow localization and tracking

(Figure 1). This work is being written up, first as a technical report and then for journal publication. The algorithm is now ready to be run on a larger sample of data that will form the case study.

Single hydrophone case studies. We have developed a framework for estimating density from counts of received sounds coupled with assumptions about source levels, directionality, propagation and detector characteristics. We have gathered the necessary inputs for beaked whales, and have completed the propagation modeling component. This work was presented at a meeting of the Acoustical Society of America, and at the Pavia conference. Work on sperm whales is ongoing.

Open meetings. We held two open meetings in 2009, one in San Diego, Californa and one in Pavia, Italy. Both comprised a tutorial overview, a series of contributed talks and a closing discussion. The meetings together were attended by approximately 120 people. full details, including talk slides are at http://www.creem.st-and.ac.uk/decaf/meetings.

RESULTS

We have published the first study demonstrating reliable estimation of cetacean density from fixed passive acoustics (Marques et al. 2009). We found density of Blainville's beaked whale over a 6-day period at AUTEC in Spring 2005 to be 22.5 or 25.3 animals/1000km^2 (coefficient of variation 20%), depending on assumptions about false positive detections. In follow-up work, using a different algorithm (dive counting) we found similar density estimates before and over 65 hours after an active sonar exercise on the range in 2008, but evidence for lower densities (or less deep-diving activity) during and immediately after the exercise. This is the first direct estimate of changes in Blainville's beaked whale density in response to anthropogenic noise and provides valuable insight into possible avoidance behavior to such disturbances. We have obtained preliminary estimates of Pacific minke whale call density; we hope in the future to combine this with an estimate of call rate to give the first density estimate for this population. Other results and findings are described in detail in the Outputs section of the decaf web site http://www.creem.st-and.ac.uk/decaf/outputs.

IMPACT AND APPLICATIONS

National Security

The US Navy is committed to marine mammal risk mitigation, both on testing ranges and exercises outside of these areas. Methods developed under this project will contribute substantially to risk mitigation capabilities, both in enabling more effective planning of testing and training for times and places that minimize exposure of marine mammals to underwater sound, and also potentially in real-time monitoring of marine mammal presence.

Economic Development

There is increasing recognition that noise in the marine environment can potentially impact cetacean populations. Important sources of noise are from shipping and from oil and gas industry seismic exploration and production. Just as for national security applications, methods developed under this project can contribute substantially to risk mitigation in industry.

Quality of Life

Cetaceans are an iconic part of the world's biodiversity; the project will enable us to better monitor their numbers and so conserve them for future generations.

TRANSITIONS

National Security

Methods and density estimates produced here for AUTEC and PMRF ranges

Quality of Life

Methods developed under this project are being applied to determine abundance of the endangered Baltic Sea harbor porpoise subpopulation (SAMBAH project – see below).

RELATED PROJECTS

- The N45 and ONR-funded Marine Mammal Monitoring on Navy Ranges (M3R) program has developed tools capable of detecting and tracking marine mammals in real time on Navy ranges (see proposal). Archival and new data from this program is being used to provide much of the input data for the current project.
- US Navy Pacific Fleet and Office of Naval Research have funded PMRF data collection and analysis, including a manual analysis of acoustic snapshots of data that forms the basis for a 'quasi ground truth' for evaluation of the minke whale and humpback studies.
- Office of Naval Research funds a project, led by Mr Tom Norris, to investigate the vocal behavior of minke whales in Hawai'i.
- The UK Defense Science Technology Laboratory (DSTL) is funding a PhD student based at UStA from 2007-2010, co-supervised by Thomas, John Harwood (UStA) and Chris Clarke (Cornell), to work on estimation of cetacean density from sparse arrays of hydrophones, such as those of the IUSS SOSUS array.
- The European Union Life+ program has funded a project, SAMBAH, to determine abundance of the endangered Baltic Sea harbor porpoise, using methods developed by this project.

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Buckland, S. T., Anderson, D. R., Burnham, K. P., Laake, J. L., Borchers, D., and Thomas, L. 2004. *Advanced Distance Sampling*. Oxford University Press, Oxford.

Efford, M.G., Dawson, D.K. and Borchers, D.L. 2009, Population density estimated from locations of individuals on a passive detector array. *Ecology* 90: 2676–2682.

PUBLICATIONS

Please note that all project outputs (including talk slides, and outputs from previous years) are available at the DECAF project web site: http://www.creem.st-and.ac.uk/decaf/

Marques, T.A., L. Thomas, J. Ward, N. DiMarzio, P. L. Tyack. 2009. Estimating cetacean population density using fixed passive acoustic sensors: an example with beaked whales. *Journal of the Acoustical Society of America* 125: 1982-1994.

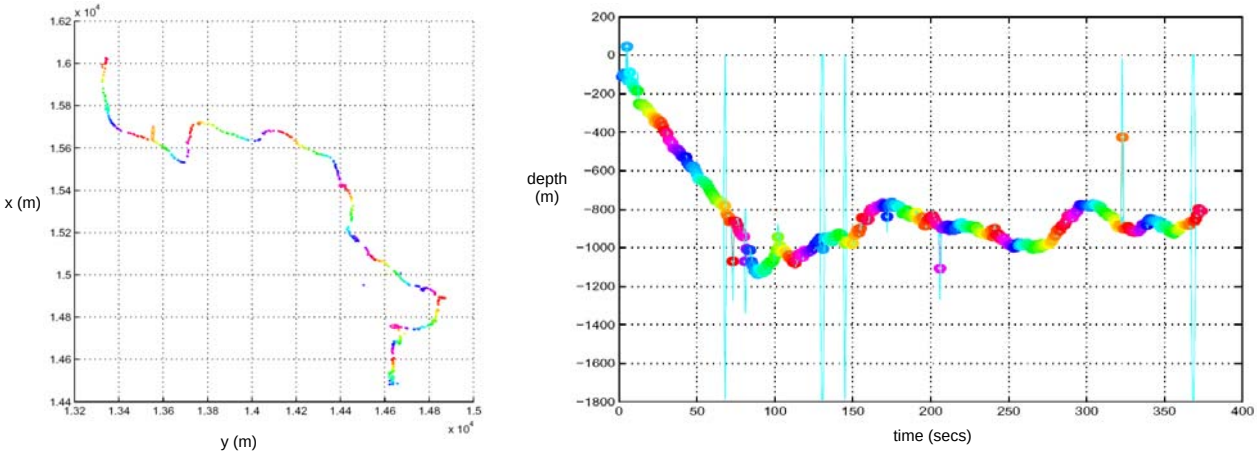

Figure 1. Example of successive 3-dimensional localizations of click trains from a single diving sperm whale at the AUTEC range, estimated using the new click separation and localization algorithms with bottom-mounted hydrophone data as input. Each colored circle represents an individual localization. The left plot shows estimated horizontal position, the right plot shows estimated depth (with confidence bounds on depth in blue). Results are from Baggenstoss (in preparation).